

Article

Incorporating Spectral Unmixing to Estimate Carbon Sequestration Changes in an Urban Forest Canopy

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Abstract

The urban forest canopy provides critical ecosystem services, including carbon storage and sequestration. Healthy, well-managed trees in an urban setting can provide these services in a way comparable to forests managed for production or as nature preserves. Disturbance events threaten these benefits by reducing canopy cover and biomass. A tornado struck Ruston, Louisiana, on 25 April 2019, resulting in severe canopy damage through a swath of the city. We used iTree Canopy to obtain estimates of ecosystem services (carbon sequestration, etc.) and converted this to a per-pixel value before interpolating for the study area. Fractional vegetation estimates obtained from spectral unmixing were obtained from pre- and post-tornado images using Sentinel-2 data and applied to weight damage. Pre- and post-tornado assessments revealed that Ruston's urban forest canopy sequestered 85% of its pre-storm capability, with an estimated decline in social value of approximately \$36,000. Assessing disturbance-based landscape changes, and subsequently calculating fractional changes in biomass and corresponding monetary impacts, will increasingly be looked to as ecosystem services and severe weather events are expected to become more commonplace in the future. The methodology employed demonstrates a cost-effective way to assess disturbance impacts in small urban areas, offering a framework to small municipalities to monitor canopy dynamics.

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1. Introduction

Urban environments are provided with numerous benefits from urban forests and trees. Quantifiable benefits exist in improvements to health and safety as well as recreational opportunities [1–4]. This was particularly true during lockdowns caused by the recent pandemic [5]. Urban trees also provide landscaping and esthetic value, and landscape managers and urban planners must consider the visual composition and conditions of planted trees and how urban trees and green spaces are viewed by the urban population [6]. Collectively, the urban forest canopy serves to mitigate the impacts of increased temperatures in populated areas, alleviate pollution, intercept rainfall and runoff, and sequester and store carbon [1,2,7]. Increased biodiversity from trees and green spaces in urban environments is also a welcome benefit as this aspect gains consideration in conservation planning [8]. There are also market benefits related to timber products [4] and there is evidence that when trees are within the line-of-sight, property values are increased [9].

Previous research has found interest in monetizing carbon storage and sequestration in the form of carbon credits [10].

Monitoring and quantifying the urban forest canopy has received much attention, from neighborhood green spaces to urban parks to total canopy cover and street trees [1,7,11,12]. As much as citizens and municipal leadership value the urban canopy, there is no large-scale plan implemented for the management of urban forests [13]. Many enjoy urban green spaces such as parks and walking/hiking trails [1,3], and these areas require maintenance and observation. Similarly, street trees provide the benefit of shade but can also impact nearby property, such as sidewalks, homes, and vehicles, and overhanging limbs and root systems need to be monitored [12]. Disturbances impact the urban canopy as well as large-scale forests. Urban trees have been impacted by Dutch elm disease, emerald ash borer, and southern pine beetles, with varying impacts on the health and mortality of the canopy [14,15]. Small- and large-scale wind events can cause devastating destruction to urban forests and leave lingering health and esthetic impacts to remnant trees [16–18].

Assessing the impacts and actions following disturbance is an important factor in urban forest management, particularly considering debris removal, the health of remaining trees, and new species selection and planting [19]. While large urban areas may employ arborists to manage and maintain the urban canopy and green spaces, smaller micropolitan areas may not have the budget to support this profession. In such cases, a means of monitoring the status of the urban canopy is needed. Remotely sensed data has been widely utilized to monitor the health of forests, as well as that of the urban canopy [7,20]. Imagery provides a way of assessing pre- and post-event changes, utilizing change detection techniques [21]. Pixel-level biomass estimates can be determined for various land covers and then assessed if/when change occurs. In large-scale events, post-classification change detection can determine the impacts of disturbance events such as hurricanes or insect outbreaks [22,23]. These datasets can be utilized to focus treatments [24] or provide damage estimates for disaster declarations and the operational salvage of timber. A limitation, however, is that class changes are assumed to be total—i.e., forest class changes to open field, where forest is assumed to be a total loss.

Urban trees require assessment when damaged by storms or other causes to determine whether treatment is required for public safety. This is particularly true in large-scale damage events and when other infrastructure has sustained damage [15–19]. Remotely sensed data can be utilized in such cases. The present study seeks to provide a method for (1) determining a micropolitan's urban canopy impacted by a severe weather event, (2) assessing the fractional composition of forest canopy in the affected area, and (3) quantifying the physical carbon and economic losses resulting from canopy change. This will provide useful information for quantifying fractional changes in vegetation composition future disturbances.

2. Materials and Methods

The study area was the City of Ruston, located in north-central Louisiana along Interstate 20. Ruston occupies 54.75 km² with a population of 22,295 (<https://www.census.gov/quickfacts/rustoncylouisian>, accessed on 15 August 2025). Its urban forest canopy occupied 41% of the area within the city limits [7]. The city was impacted by an EF3 tornado (wind speeds between 219 and 266 kph) in the early morning of 25 April 2019 (<https://noaa.maps.arcgis.com/apps/MapSeries/index.html?appid=68671bcbbeaf483f896c70845538d1fa>, accessed on 5 September 2025). The tornado touched down multiple times in the central portion of the city, including residential areas and the campus of Louisiana Tech University, destroying homes and impacting the urban canopy. The majority of the impacts from this event, including fatalities, happened along an approximately 7.5 km

portion of the city where the storm was most destructive, impacting an area approximately one-kilometer wide (Figure 1a,b).

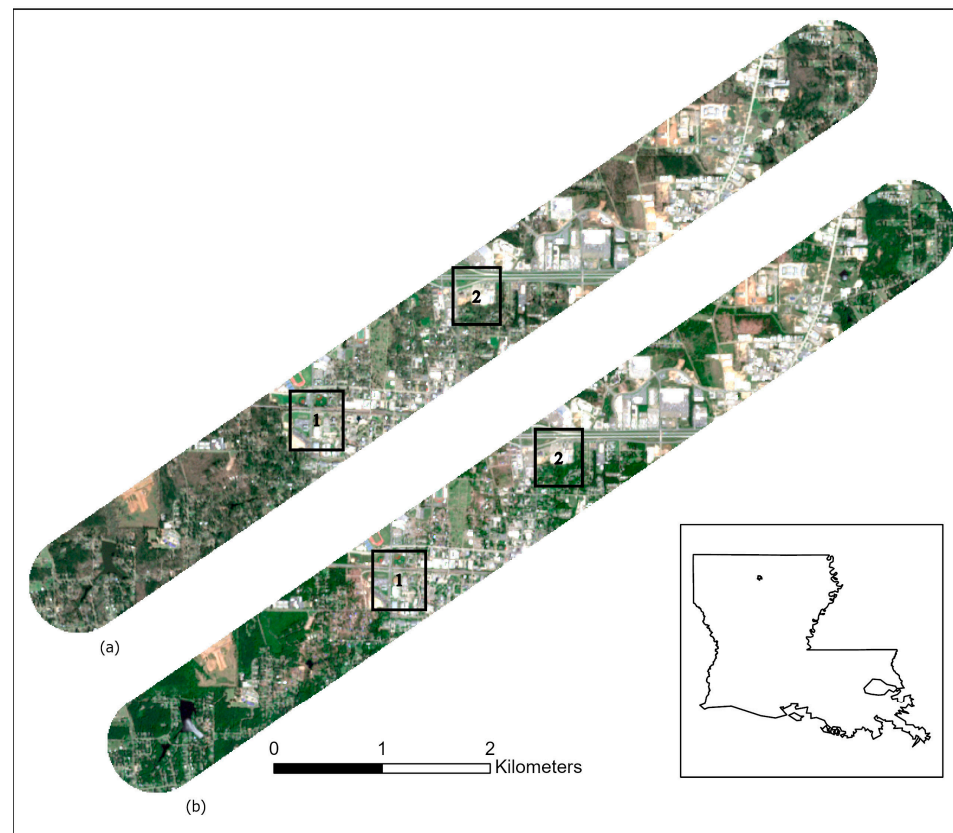


Figure 1. Study area showing the portion of Ruston, LA, in north-central Louisiana impacted by the EF-3 tornado. Sentinel-2 image from March 2019 (a) prior to the storm and May 2019 (b) after the storm. The area marked (1) is part of Louisiana Tech University and (2) is the approximate location of Interstate-20.

Remotely sensed imagery was acquired from the Sentinel-2 satellite, operated by the European Space Agency and made freely available (<https://dataspace.copernicus.eu/explore-data/data-collections/sentinel-data/sentinel-2>, accessed on 23 May 2024). Given the small scale of the present study, the 10 m spatial resolution of the visible (i.e., red, green, and blue) and near-infrared (NIR) reflectance bands were selected, as they provided the most detail available quickly and freely. Imagery was obtained for 15 March 2019 (pre-storm) and 4 May 2019 (post-storm), and the maximum width of the tornado [25] was used to create the area of interest (AOI) for detailed assessment.

Linear spectral unmixing (LSU) was performed on the imagery to elucidate the fractional composition of each endmember (pixels representing tree canopy, grass, and urban) for the pre- and post-storm periods. The unmixed pixels provide the percentage of each pixel belonging to selected land cover types. When changes occur to forest land cover, whether due to land use or disturbance, canopy change can be determined, which can then be extended to an estimated mass of carbon. Specific to the Ruston tornado, those changes were linked to social dollar-values. The change in fractional composition provided a means of calculating changes in biomass post-tornado. In cases where the tornado did not lead to tree mortality but did defoliate or break portions of the crown, the fractional composition of vegetation would not necessarily go to zero. Areas of known composition (i.e., known land cover types—tree/forest, grass, bare ground/urban) were selected based on the criteria above and LSU was performed in ArcGIS Pro software (version 2.8). Known

endmembers for tree, grass/short vegetation, and bare ground and asphalt/roof (called urban) were selected using known/marked locations from along the tornado track (i.e., the areas used for endmembers were identified on a NAIP image and visited in situ to validate the cover type before using with the Sentinel imagery). The LSU creates an x-band result of proportional land cover in each pixel based on the linear combination of reflectance values for that pixel and the relative amount of each land cover class/endmember (Equation (1)):

$$v_i = \sum_{j=1}^n (a_{ij}x_j) + e_i \quad (1)$$

where v_i is the reflectance of the mixed pixel, a_{ij} is the reflectance of the endmember j in band i , x_j is the amount of each endmember j in a pixel, and e_i is the error term for band i [26].

The result is a corresponding x-band image of proportional outputs for each chosen endmember. For example, one could select three cover types/endmembers for an input image. The output is a three-band image with the proportion of each endmember as a separate band (in this study, tree, grass, and urban). The proportion of tree cover in each pixel was then extracted to use as a weight on per-pixel biomass estimates. For example, if a pixel contained one-tonne of carbon and was found to be 40 percent tree/forest, then the weight $0.4 \times 1 \text{ tonne C} = 0.4 \text{ tonne C}$. This provided a means of overcoming the limitation of assuming total loss for changed pixels, as is the case in post-classification change detection. Biomass and carbon changes were instead based on weighted per-pixel values.

Unfortunately, there were no available datasets on tree measurements or area-based estimation for tree biomass in the City of Ruston prior to, or following, the storm. To compensate for the lack of in situ data, we simulated a dataset using random samples pre- and post-tornado. Carbon storage and sequestration were estimated using iTree Canopy (Version 7.1) [27,28] by importing the buffered tornado track (i.e., AOI) into the program. Using this polygon to define the study area, 50 random samples were allocated to each class (i.e., tree, grass, and urban/non-vegetated), which match the selected endmembers for the spectral unmixing process. These 150 total samples were classified by the user using a visual interpretation of high-resolution aerial imagery. To obtain pre- and post-storm coverages, the plots were exported to Google Earth Pro (Version 7.3) and pre- and post-tornado imagery was utilized to classify the sample locations. The random plots, after classification in iTree, were found to contain 71 points that were determined to contain tree canopy. iTree uses the canopy cover estimates from the sample locations to calculate the percentage of tree canopy in the defined study area. The carbon storage and sequestration calculations were then performed using average allometric equations for biomass [11,29], and the social value of carbon, which was approximately \$188/t at the time, used to estimate dollar values [29]. The plots were exported and biomass values were allocated to the plots for the 2018 (pre-tornado) imagery.

Exported plots were interpolated for canopy/tree cover using an Inverse Distance Weighted method to obtain carbon sequestration estimates throughout the study area (Equation (2)). These values provided a 'pure' per-pixel estimate of ecosystem service values. The values from iTree Canopy were then converted from the estimate provided in square kilometers of study area into per-pixel values, then divided evenly among the 71 point locations classified as tree canopy cover.

$$z_p = \frac{\sum_{i=1}^n \left(\frac{z_i}{d_i^p} \right)}{\sum_{i=1}^n \left(\frac{1}{d_i^p} \right)} \quad (2)$$

where z_p is the interpolated value, z_i are point values, d is the distance between points, and p is the power function (the amount of influence a point value has on interpolated values nearer to the point).

The fractional component of tree cover from LSU was then used to weight the interpolated carbon sequestration value for a pre-tornado carbon sequestration value. This yielded the per-pixel carbon value (in kilotons) throughout the study area. This was repeated using the fractional portion of forest for each pixel based on the post-tornado image (from May 2019). Finally, the values were subtracted from the earlier dated image (March–May) to obtain a total change estimate for the study area in Ruston. The assumption was that, for example, if one tonne of carbon existed in a pixel before the tornado and it was 100% tree, there was one tonne before the tornado. If the proportion changed to 70% tree post-tornado, then 0.7 tonne carbon existed. The limitation of formerly assuming a total loss—one tonne of carbon—was overcome.

3. Results

Trees covered approximately 47% of the study area pre-tornado (grass was approximately 23% and urban 30%). This decreased to nearly 40% of the area post-tornado (with grass and urban occupying approximately 60% of the area). The McNemar test, calculated at $\alpha = 0.05$, indicates a significant decline in tree canopy in the study area. Carbon storage in biomass and sequestration decrease by 4.25 kt and 0.22 kt/km²/y, respectively (Table 1). The pre-tornado LSU image showed the tree canopy in the area of Ruston impacted by the tornado with full tree canopy. Grass in open areas was also noticeable, as were areas of bare ground and urban areas including homes, roads, etc. The per-pixel proportion covered by tree canopy have percentages ranging from 0 to 100%, where 100% were likely to be mature pine stems in wooded areas or those clustered within neighborhoods (Figure 2a). The post-tornado area assessing the same location shows the per-pixel percentages of tree following the tornado (Figure 2b). It is also noteworthy in this result is that there is not a binary change/no-change occurring, but the fractional proportion of each pixel allows for the determination of biomass and associated carbon content to still be calculated.

Table 1. Carbon storage and value changes to the urban tree canopy following the 2019 Ruston, LA, tornado.

	Pre-Tornado	Post-Tornado
Carbon Stored (kt)	30.27	26.01
Carbon Value (million USD)	5.69	4.89
Carbon Sequestered (kt/km ² /y)	1.56	1.34
Carbon Value (million USD)	0.292	0.252

Fractional changes in carbon sequestered, per pixel, in Ruston were calculated using interpolated carbon sequestration values with LSU values as a weight. The total estimated carbon sequestered was slightly more conservative than the estimate provided by iTree Canopy. The iTree results yield a pre-tornado carbon sequestration total of 1.56 kt and a post-tornado total of 1.34 kt. Using the LSU endmembers, the pre-tornado carbon sequestration total was 1.28 kt and the post-tornado total was 1.09 kt, a reduction of 15% (Figure 3a,b). It is also worth noting that the iTree and LSU-derived differences show the same percentage change in the aftermath of the tornado. Regardless of the differences, the decrease in sequestration potential will take many years to replace, as replacement trees will require time to grow to maturity.

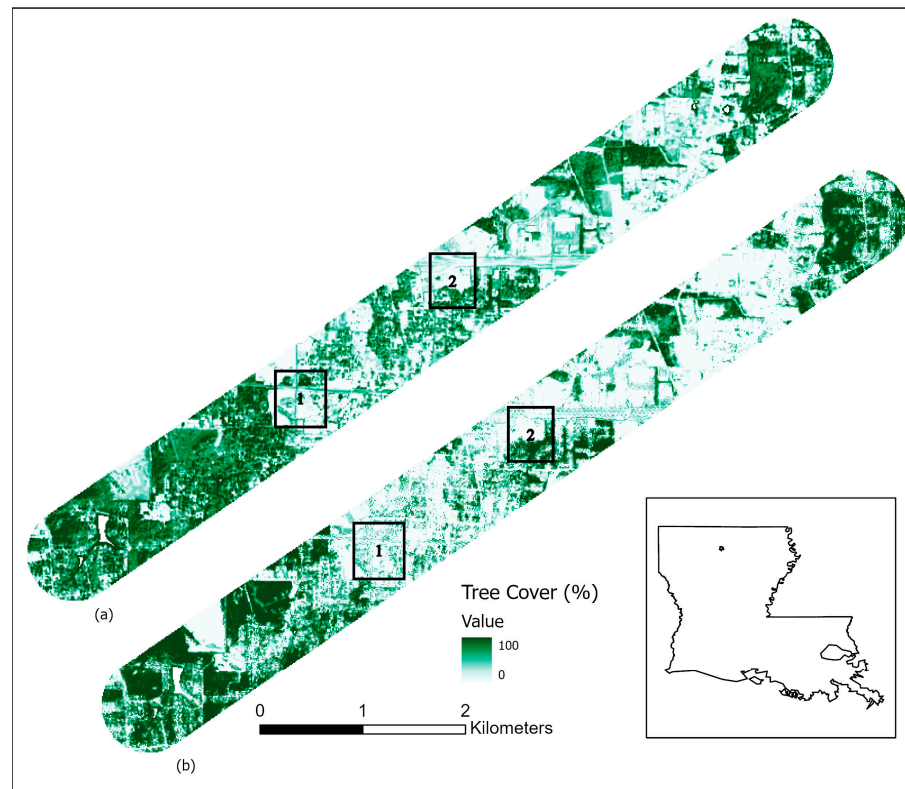


Figure 2. Per-pixel percentages of tree in (a) March 2019, before the tornado and (b) May 2019 after the tornado. The area marked (1) is part of Louisiana Tech University and (2) is the approximate location of Interstate-20.

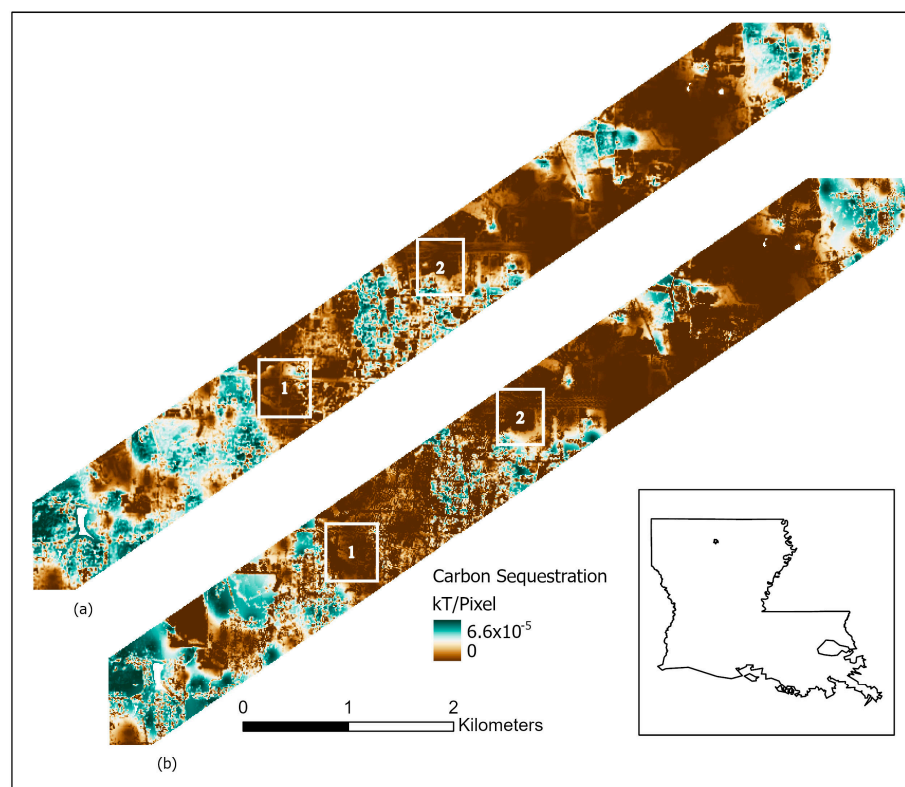


Figure 3. Carbon sequestration rates in (a) March 2019, before the tornado and (b) May 2019 after the tornado. The area marked (1) is part of Louisiana Tech University and (2) is the approximate location of Interstate-20.

The tornado intensified, moving northeast towards the university and then the area immediately surrounding the interstate; tree damage in this area was nearly total. North of Interstate-20 were areas where many trees were toppled but also where only partial changes occurred. This was primarily along the tornado's north edge as it tracked northeast (Figure 3b). Visually, the greatest change in vegetation and carbon sequestration potential occurred in the residential area near Louisiana Tech's campus northeast to near Interstate-20, where street patterns can be observed following tree damage and losses due to the tornado (Figure 4a). The LSU-weighted results show a decline in socially valued carbon sequestration of \$36,400, highlighting damage in neighborhoods and along roads. Also noteworthy was the increase in value some areas that likely saw little damage, experienced along with the continued greening of further into the spring (observable by the negative values in Figure 4b).

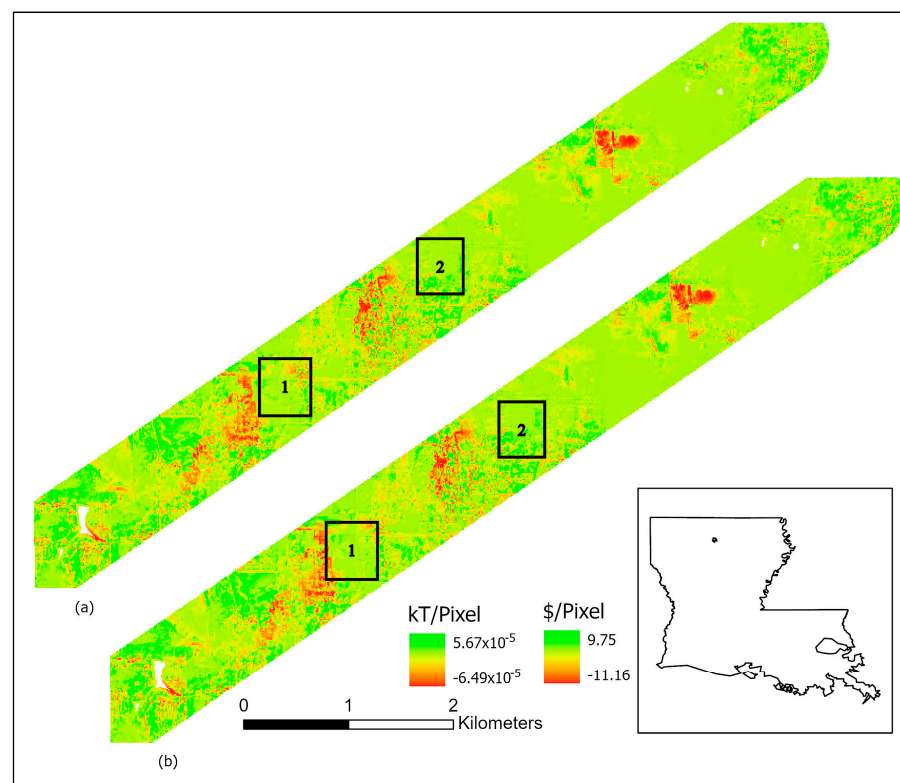


Figure 4. Changes in carbon sequestration (a) and dollar value (b) losses due to the tornado. Greener shades are positive changes while redder shades are negative changes (i.e., the areas were not impacted and continued growth occurred). The area marked (1) is part of Louisiana Tech University and (2) is the approximate location of Interstate-20.

4. Discussion

The LSU method detected proportional/non-total changes in canopy cover, resulting from a tornado impacting Ruston, LA. Using iTree Canopy's estimates for urban forest canopy benefits provided a means of quantifying these values and the impacts of change on the urban canopy. Converting carbon sequestration to per-pixel estimates and using the pixel's proportion that is tree cover as a weight provided a more conservative estimate than iTree Canopy's total tree cover assumption. Doing so produced fractional estimates of change rather than whole pixel changes—changes that may or may not necessarily occur. This offers greater precision than simply concluding whole-tree/forest changes. More accurately estimating carbon sequestration impacts following natural disasters can

provide municipalities with a low-cost means of adequately assessing vegetation viability in damaged areas.

The fractional composition of tree cover in each pixel determined through LSU allows us to assess whether there was a partial or total compositional change following the passage of the tornado. Using the spectral endmember for tree as a weight, a decrease in carbon sequestration of 15% was revealed, along with a reduced proportion of tree canopy cover, ranging from no change to total canopy loss. The fractional composition of a pixel in terms of tree canopy is an important component of accurately assessing carbon content [30], and its value here was evident. The more conservative values were not unexpected compared to iTree or allometric equations on whole trees in such settings because of the biomass weighting, which used the spectral endmember for the percentage of each pixel that was tree. More realistic estimates compared to a binary change detection help to better inform those that may be involved in carbon trading and policy decisions. Disturbance impacts are not universal either; tree growth–carbon relationships vary due to site, species, and disturbance agent. Understanding these differences beforehand can improve accuracy when estimating an area’s impacted portion that was covered by trees.

Correctly identifying the spectral endmembers is essential. Time of year, mid-spring for this application, could present some challenges for endmember selection in remote or unknown environments. In the present study, Ruston has parks and areas of forest that were used for endmember selection. Care must be taken to only select pure endmembers to avoid misrepresenting the proportion of the endmember/land cover classes to be studied. It would also benefit users to obtain field-based spectral data or assess canopy openness. That may allow for more effective endmember selection. The urban canopy’s role in carbon offset programs has been reported [8]. Integrating remotely sensed methodologies into the monitoring process will aid in maximizing the benefit of urban forest systems by providing an efficient means of gathering data for analysis.

The 10 m resolution used for this assessment was adequate. Using higher resolution imagery (e.g., WorldView or NAIP) may improve classifying changes in tree canopy but would incur greater cost in terms of manual interpretation, training object classifiers, and processing times. Acquiring imagery can also be expensive. Freely available imagery coupled with unmanned aerial vehicles (UAVs) could make monitoring more affordable for those with the skills to analyze the data [15]. These data also provide archived information that can be utilized to track patterns of change. Urban forest managers and planners could benefit from creating a database of imagery and using it to track small-scale changes in the urban canopy and related influences on property values [9,29]. Further, property values impact property taxes, which impact government services for all citizens. Given the object detection capabilities and artificial intelligence methodologies, it may be possible in future to use these tools to provide near real-time updates on the urban canopy.

Urban planners and leadership may also find value in conducting preliminary assessments of their urban canopy using the iTree suite of products, which are freely available [<https://www.itreetools.org/>, accessed on 10 August 2025]. iTree Canopy, specifically, provides a means of obtaining baseline estimates of the benefits of the urban canopy [7,11]. However, it is also important to conduct an inventory of the urban environment. Such datasets can be combined with local meteorological observations in other iTree products and rainfall mitigation, etc., added to the consideration of the benefits and changes in the urban canopy [12]. A limitation of this study is that there was no pre-storm urban inventory. While the regional approach to biomass estimation provided by iTree Canopy is valid [11], it would help improve estimates if we calculated local biomass estimates. The interpolation of these values is sometimes viewed as a potential shortcoming, but Munyati and Sinthumule [31] found that IDW performed better than other methods when

interpolating less dense forest savannahs. While that is likely the case in urban settings, given the sparse arrangement of clusters of trees, further research could better elucidate this relationship and the applicability of larger-scale estimation using interpolation methods.

Urban forests are an important part of carbon dynamics globally. This does not mean to imply only large cities and metropolitan areas are the sole contributors. Indeed, municipalities of all sizes comprise varying proportions of built and natural environments. Smaller urban areas have been found to have significant coverage by trees and green spaces [7] with much of this area likely owing to natural growth and development. These areas, and not just large urban centers, could benefit from coordination across multiple entities and scales of management, as suggested by [19]. This methodology also provides a way to assess fractional vegetation cover to find areas suitable for tree planting. This is important for urban planners, as site selection is an important first step in managing the urban canopy. Critically, urban managers need to be aware of species characteristics for survival and growth [32] and make an effort to mitigate the impacts of damage from disturbance [33]. Consideration should also be given to the changes in carbon sequestration and storage and the time-lag that exists for re-establishment of trees damaged or lost due to disturbance. iTree also contains methods for estimating other gas sequestration such as NO_x and SO_x , as well as particulate matter in the atmosphere. The approach used in the present study could also be expanded to determine the impact of canopy changes on these other important variables, particularly in larger urban centers where they have a relationship with breathing stress and other human impacts [2,5,20,32].

Modeling disturbance impacts on the carbon sequestration potential of the urban canopy requires understanding canopy damage and how to assess it. This also has applications for stand-level disturbance from many modes of disturbance (e.g., wind, insect, thinning, etc.) and could be incorporated into assessing forests' carbon pools combined with plot-level inventory data. In larger systems, such as a multi-unit forest, portions lost to disturbance or harvest would experience reduced carbon pools [34]. Spectral unmixing would provide a remotely sensed method of assessing the economic impact of such changes when field assessment may not be possible. Future studies can apply this method to larger-scale disturbances (e.g., hurricanes, extreme wind events, etc.) to assess salvage operations occurring in the aftermath of a disturbance by estimating the composition of downed material/bark [35]. Future study could also assess additional mortality, removals, or replanting that occurs following disturbance. Annual, systematic assessments of biomass for carbon offset programs provide information regarding growth, drain (harvest), or other tree- or forest-level intrusions. It is suggested that municipalities with a high percent coverage of urban canopy make efforts to inventory these areas and maintain health assessments, which can be at least partially monitored using remotely sensed data. The spectral proportion of a pixel provides a means of intermediately determining conditions following disturbance [20,35,36].

5. Conclusions

This study demonstrated linear spectral unmixing to quantify proportional changes in tree canopy following a severe weather event. By integrating fractional canopy cover derived from Sentinel-2 imagery with carbon estimate from iTree Canopy, we were able to capture partial canopy changes rather than assuming a total change (as with post-classification change detection). This produced a more conservative and realistic estimate of carbon sequestration decline (~15%) and associated social value losses (~USD 36,000) following the 2019 tornado. The tradeoff with labor intensity is accuracy when assessing changed conditions, but this method also provides a way to determine damage and deploy

personnel to assess additional impacts. This could be utilized in urban and production forests for monitoring biomass/carbon as carbon accounting programs continue to evolve.

This study illustrates that utilizing freely available remotely sensed data and open-source tools can provide municipalities with cost-effective means of monitoring ecosystem services and losses from disturbance. The results are important for urban planners, foresters, and policymakers seeking to account for carbon dynamics, justify investments in urban canopy management and tree recovery, and enhance urban climate resilience. Future studies should consider not only monitoring the health of the urban canopy and susceptibility to disturbance but also the continued esthetic and biological roles the canopy plays. Focus should be given to the current composition of urban forests and species selection for newly established trees. Regular assessment of the benefits provide by urban forests is also important, as well as potential impacts of projected climate change. Urban planners and managers should consider the role of remotely sensed data and analysis to help maintain the integrity of the urban canopy.

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Data Availability Statement: The remotely sensed data and iTree Canopy are both freely available online and are reference in the manuscript.

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